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A STUDY OF CLOSED LOOP CONTROL OF ACTIVE TAB WITH BVI DETECTION METHOD FOR HELICOPTER NOISE REDUCTION

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Abstract: This paper presents the research activities of a control law study applicable to active technique for rotor noise reduction. In order to develop an active noise reduction technique, it is essential to invent a promising active devise. But it is also imperative to develop a control law applicable to active technique corresponding to time varying flight conditions and able to generate proper set of operating quantities such as frequency, amplitude and phase promptly. Furthermore, we focused on the blade surface pressure as a control input, because this enables the control system to be made only by on-board sensors with BVI detection method. The sound pressure is also measured not as an input to the control law but for evaluating the performance of the control law.

The performance of this proposed closed loop controller was evaluated in a wind tunnel test using 1-blade rotor system equipped with Active Tab as an active technique. It is demonstrated by this wind tunnel test that the control law utilizing the blade surface pressure successfully functioned to make use of Active Tab capability to reduce BVI noise with sufficient convergence.

1 INTRODUCTION

Helicopters are used in a various scenes where we can realistically feel the utility of helicopters. But due to the noise problems, helicopters can be operated only on constrained conditions. The technological solutions have long been desired which can obtain public acceptance by highly reducing the noises emitted around heliports and beneath flight paths and can clear ICAO noise regulation getting more stringent with sufficient margin.

In such a context, several organizations and helicopter manufacturers have been conducting to invent novel technology to reduce helicopter noise, especially BVI noise. [1-5]

JAXA started a research activity for a new active technique for rotor noise reduction under a joint research program with Kawada Industries Inc. This new technique is referred as “Active Tab”. This research program comprises of four steps such as 2D wind tunnel testings, CFD, rotor testings and a control law development as shown in Fig.1.

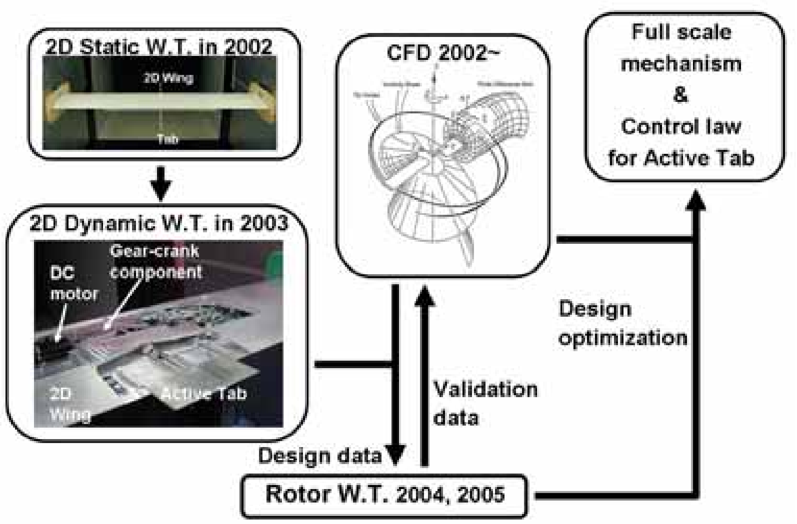


Figure 1: Active Tab research program

For the purpose of constructing a closed loop control law, we developed an elemental closed loop control law as the first step and evaluated by a wind tunnel tests in 2003 and 2004. [6] This control law utilizes the sound pressure measured by microphones as an input.

Using the sound pressure as an input to the control law for noise reduction, it is necessary to install microphones on the aircraft or on the ground. The former may pick up the noise irrelevant to the BVI, and the latter needs the up-link infrastructure which transmits the measured sound pressure to the aircraft in the air. Therefore, the both seem to be inefficient and challenging because of requirement for other technical resolutions in the phase of practically applying to the helicopters.

We noticed and try to utilize the blade surface pressure as an input to the control law on this background to construct an efficient control system, because the BVI phenomenon is clearly characterized by abrupt temporal changes of the blade surface pressure which can be measured by pressure transducers installed on the blade.

This paper describes the research activities of the control law study and its evaluation by a wind tunnel test performed in 2005.

2 ACTIVE TAB RESEARCH PROGRAM

The schematic view of the active tab is shown in Fig.2. The active tab is installed in the aft portion of the airfoil and driven back and forth dynamically to reduce BVI noise and the vibration by the blade circulation control due to the variable blade area effect.

As shown in Fig.1, we started in 2002 to study the fundamental tab aerodynamic property by a 2D static wind tunnel test, and then proceeded to 2D dynamic wind tunnel test in 2003 to examine the tab dynamic effect. This step of the study showed that a realistic size and anhedral of the active tab has sufficient aerodynamic capability equivalent to the potential for rotor noise reduction [7]. CFD analysis simultaneously started to propose aerodynamically effective tab geometry [8].

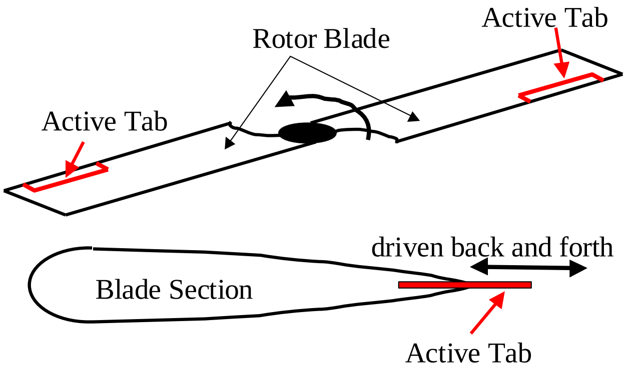


Figure 2: Active tab concept

In 2004 and 2005, the rotor wind tunnel tests were carried out in a rotor configuration with on-blade active tab to evaluate the active tab effect on rotor noise reduction and to provide the validation data for CFD code development. It is demonstrated by this wind tunnel test in a rotor configuration that the active tab has the efficient capability to control the rotor noise about 3dB and that the active tab is one of the promising techniques for rotor noise reduction as shown in Fig.3 [9,10].

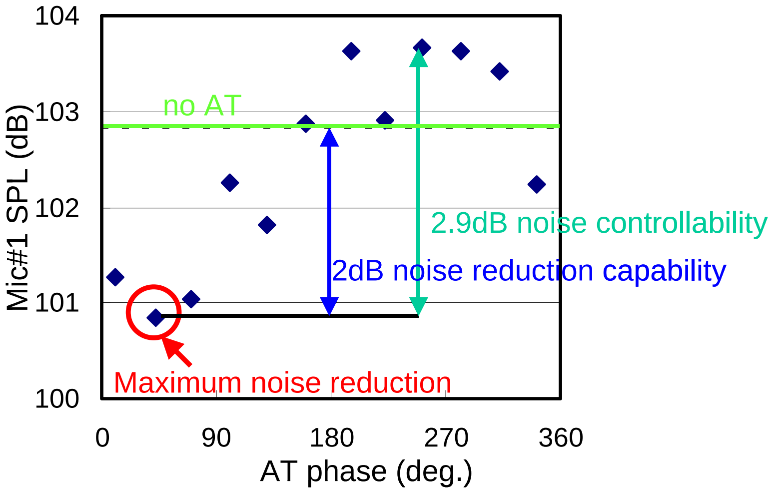


Figure 3: Active Tab effect for rotor noise reduction

The control law applicable to active technique corresponding to time varying flight conditions and able to generate proper set of operating quantities such as frequency, amplitude and phase promptly are also essential. We focused on the blade surface pressure as a control input based on previous studies [10,11], because this enables the control system to be made only by on-board sensors with BVI detection method.

3 OBJECTIVES

The objectives of this research are as follows;

1. Develop and evaluate a control law for the active technique utilizing the blade surface pressure, which enables the control system to be made only by on-board sensors.
2. Study a proper procedure to process the blade pressure data as an input to a control law which is easily contaminated by electrical noise.

4 CONTROL LAW

In order to evaluate BVI relief effect with respect to AT phase, the pressure fluctuation index ΔCpmax which physically means the maximum value of the difference in the pressure coefficient between the successive ψ's is introduced and defined as shown in Ref.12, which is repeated below for convenience.

$$\begin{aligned} &\Pr essure\,Fluctuation\,Index: \Delta C_{p\max} = \max(\Delta C_p(\psi_i)) \\ &\Delta C_p(\psi_i) = C_p(\psi_i) - C_p(\psi_{i-1}) \\ &\psi_i - \psi_{i-1} = 0.9\,\mathrm{deg}. \\ &C_p = \frac{P - P_s}{q} \end{aligned} \tag{1}$$

where

P : measured blade surface pressure
Ps : static pressure
q :dynamic pressure at 85%R as V_W=0m/sec, rotor speed=600rpm

The effect of AT phase on ΔCp is shown in Fig.4 as the relationship between ΔCpmax and the whole range of AT phase.

Studying Figs.3 and 4 together, the correlation between the sound pressure level and ΔCpmax with respect to AT phase can be seen. AT phase range around 90deg. simultaneously has the largest rotor noise reduction indicated by the sound pressure level and the maximum BVI relief effect by ΔCpmax. This characteristic of ΔCpmax with respect to AT phase is useful as an input to the control law for Active Tab, because the BVI can be detected and evaluated by only on-board sensors.

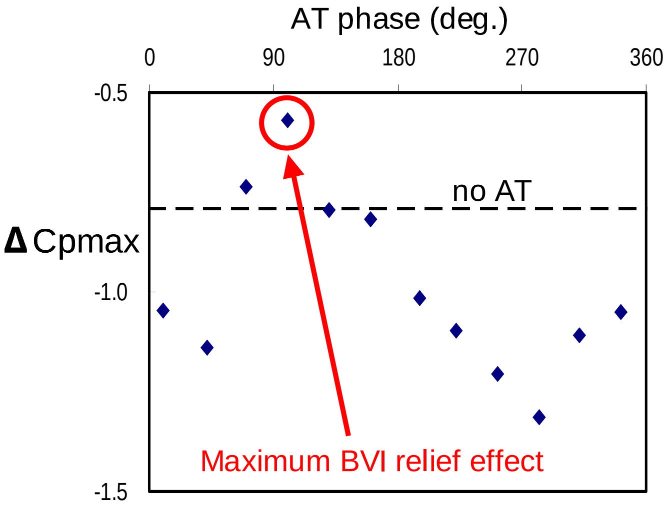


Figure 4: Active Tab phase effect on ⊿Cpmax

In this study, a global model is used to represent the relationship between the plant and the control input, although a local model also can be defined for this study. Because it is shown by the wind tunnel test that the correlation between ΔCpmax and AT phase as shown in Figs.3 and 4 is stable so that the transfer function can be assumed invariant over the control cycles. This yields the following T-matrix global model:

$$Z_n = Z_0 + T\theta_n \tag{2}$$

θ_n represents Active Tab input vector consisting of frequency, amplitude and phase. Therefore, the number of the components in this vector is generally double the number of the frequencies superposed to the blade pitch control to express amplitude and phase of each frequency of AT. In this study, however the 1-bladed rotor system which is used for the control law evaluation can only automatically change AT phase by the mechanical limitation.

Although this enables θ_n to be a scalar not a vector, we proposed the following transformation for θ_n to make use of the empirically obtained sinusoidal property of ΔCpmax with respect to AT phase shown in Fig.4, which is to avoid redundancy for solving θ_n.

$$\theta \equiv \begin{bmatrix} \cos\phi_{AT} \\ \sin\phi_{AT} \end{bmatrix} \tag{3}$$

where

ϕ_{AT} : Active Tab phase

Making use of the correlation between sound pressure and blade surface pressure as shown in Figs.3 and 4, the quadratic performance function for the control law is proposed to utilize blade surface pressure instead of sound pressure as follows:

$$J = Z_n^T W_z Z_n + \theta_n^T W_\theta \theta_n + \Delta\theta_n^T W_{\Delta\theta} \Delta\theta_n \tag{4}$$

where

$Z_n = \Delta Cp_{\max}$

W_Z : weighting matrix for Z

θ_n : control input representing Active Tab frequency, amplitude and phase

W_θ : weighting matrix for θ

$\Delta\theta_n$: the difference of θ between successive control cycles

$W_{\Delta\theta}$: weighting matrix for $\Delta\theta_n$

Furthermore, in order to quantify the plant property, two kinds of identification are used. The first one is off-line identification by the least square method to identify only initial values of transfer matrix T and Z_0. The other one is on-line identification by Kalman filter to identify the transfer matrix on each control cycle.

Solving the performance function to get $\partial J/\partial\theta_n = 0$ applying the global model with on-line identification:

$$\theta_n = (\hat{T}_{n-1}^T W_z \hat{T}_{n-1} + W_\theta + W_{\Delta\theta})^{-1}\left\{(\hat{T}_{n-1}^T W_z \hat{T}_{n-1} + W_{\Delta\theta})\theta_{n-1} - \hat{T}_{n-1}^T W_z Z_{n-1}\right\} \tag{5}$$

$$\hat{T}_n = \hat{T}_{n-1} + (Z_n - \hat{Z}_{0n-1} - \hat{T}_{n-1}\theta_n)K_n^T$$

$$\hat{Z}_{0n} = \hat{Z}_{0n-1} + (Z_n - \hat{Z}_{0n-1} - \hat{T}_{n-1}\theta_n)K_{zn}$$

$$K_n = P_n\theta_n/r$$

$$P_n = M_n - M_n\theta_n\theta_n^T M_n/(r + \theta_n^T M_n\theta_n)$$

$$M_n = P_{n-1} + Q$$

where

K_n : Kalman gain
P_n : covariance of error after measurement
M_n : covariance of error before measurement
Q : covariance of process noise
r : covariance of measurement noise
$^\wedge$: estimated value

The cycle to generate θ_n is repeated until the performance function sufficiently converges.

In order to obtain converged θ_n in the form of Eqn.(3), the following consideration is proposed. Taking into account measurement noise, the relationship between the plant and the control input is slightly modified,

$$Z_n = Z_0 + T\theta_n + \nu_n \tag{6}$$

where

ν_n : measurement noise

Substituting Eqn.(6) into Eqn.(5), we have

Transfer state:

$$\theta_n = (\hat{T}_{n-1}^T W_z \hat{T}_{n-1} + W_\theta + W_{\Delta\theta})^{-1}\left\{\hat{T}_{n-1}^T W_z\left(\hat{T}_{n-1} - T\right)\theta_{n-1} + W_{\Delta\theta}\theta_{n-1} - \hat{T}_{n-1}^T W_z\left(Z_0 + \nu_{n-1}\right)\right\} \tag{7}$$

Making $\hat{T}_{n-1} = T$,

Steady state:

$$\theta = \left(T^T W_z T + W_\theta + W_{\Delta\theta}\right)^{-1}\left\{W_{\Delta\theta}\theta - T^T W_z\left(Z_0 + \nu\right)\right\} \propto \left(T^T W_Z T + W_\theta + W_{\Delta\theta}\right)^{-1} T^T W_Z \nu \tag{8}$$

Studying the coefficient matrices of ν in Eqns.(7) and (8), it is inferred that the conditions described in Eqn.(9) assures the existence of θ_n without divergence by making the coefficient matrices of ν diminish as the control cycle proceeds.

$$\begin{aligned} \|G_t\| &\equiv \left\|\left(\hat{T}_n^T W_z \hat{T}_n + W_\theta + W_{\Delta\theta}\right)^{-1}\hat{T}_{n-1}^T W_z\right\| < 1 \\ \|G_s\| &\equiv \left\|\left(T^T W_z T + W_\theta + W_{\Delta\theta}\right)^{-1} T^T W_z\right\| < 1 \end{aligned} \tag{9}$$

where

G_t : coefficient matrix for ν_{n-1} for transfer state (Eqn.(7))
G_s : coefficient matrix for ν for steady state (Eqn.(8))

Satisfying Eqn.(9), it is necessary to select the combination of large W_θ and small $W_{\Delta\theta}$, which is searched practically by trial and error in the wind tunnel test to evaluate the proposed control law.

5 WIND TUNNEL TEST SET UP

This wind tunnel test was performed to study the performance of the control law applied to the 1-bladed rotor system which has Active Tab as an noise reduction active technique.

5.1 Model description

The rotor system is set up in the 2.5x2.5m low speed wind tunnel of Kawada Industries, Inc. using a one-bladed rotor system as shown in Fig.5. The main features of this rotor system are shown in Table 1.

The active tab installed on the blade and its schematic drawing is shown in Fig.6. The main features of the active tab are also shown in Table 1. The tab is fan-shaped so that the extended area generated by the tab operation is made larger in the outer portion of the blade. A 10deg. anhedral angle is put to the tab so that the tab effect to the blade lift increment is augmented based on the previous work as shown in Ref.7.

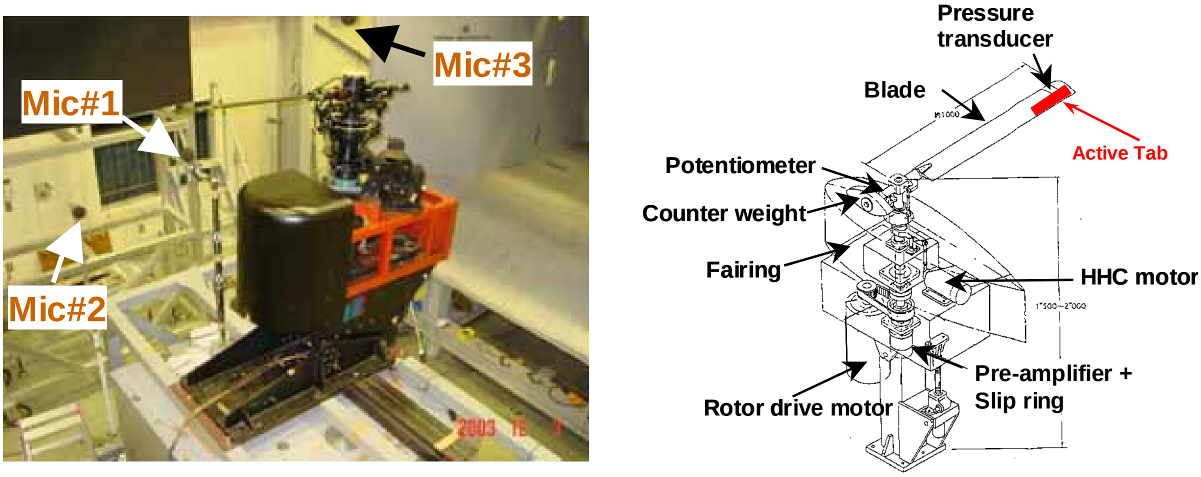


Figure 5: One-bladed rotor system

Table 1 Features of rotor system and Active Tab

Hub type	rigid in flap and lead-lag
Rotor radius	1m
Blade chord	0.12m
Airfoil	NACA0012
Blade plan form	Rectangular
Rotor rpm	1200rpm (max)
Collective pitch	-5 to +15deg.
Cyclic pitch	0deg. (fixed)
Active Tab	Amp. : 12mm(max)
	Freq. : 20Hz
	Phase : variable
	Span : 80 ~ 98%R

This active tab is pivoted at its apex to 80%R location of the blade. The end of the rack which makes the active tab move back and forth is fixed to the active tab slightly outboard side of the active tab apex so that the travel of the rack can be made as small as possible to achieve the full amplitude of the active tab motion. The other details of the rotor system and the blade with active tab are described in Ref.9.

The active tab deflection is defined as follows:

$$\delta_{AT} = \theta_{AT} \cos(2\Omega t - \phi_{AT}) \tag{10}$$

where
δ_{AT} : Active Tab deflection (deg.)
θ_{AT} : Active Tab amplitude (pre-set, deg.)
ϕ_{AT} : Active Tab phase (deg. or rad)
Ω : rotor speed (rad/sec)

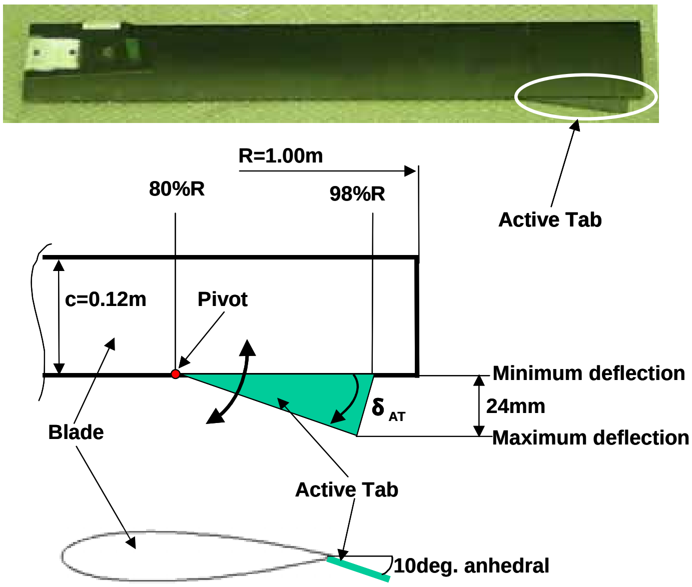


Figure6: Active Tab installation

5.2 Test condition

The test condition is as follows;

Wind tunnel
  Wind speed : 18m/sec
  Test section : open
Rotor system
  Rotor speed : 600rpm (10Hz)
  Collective pitch angle : 4.3deg
  Cyclic pitch angle : 0deg
  Rotor shaft angle : 2deg. nose up
Active tab
  Frequency : 20Hz (2/rev)
  Amplitude : 3.8deg.
  Phase : 0 ~ 360deg.

5.3 Measurement

The schematic view of the whole measurement system is shown in Fig.7.
The blade surface pressure distribution is measured by pressure transducers mainly located on the 85%R position of the upper and lower sides of the blade. Two microphones are set in the wind tunnel as shown in Figs.5 to evaluate the active tab effect for rotor noise reduction.

The active tab deflection is detected by a Hall sensor installed just inboard portion of the active tab and a potentiometer installed at the center of the rotor hub measures blade pitch angle. A pulse encoder generating 1/rev signals is installed beneath the rotor plane at about ψ=0deg.

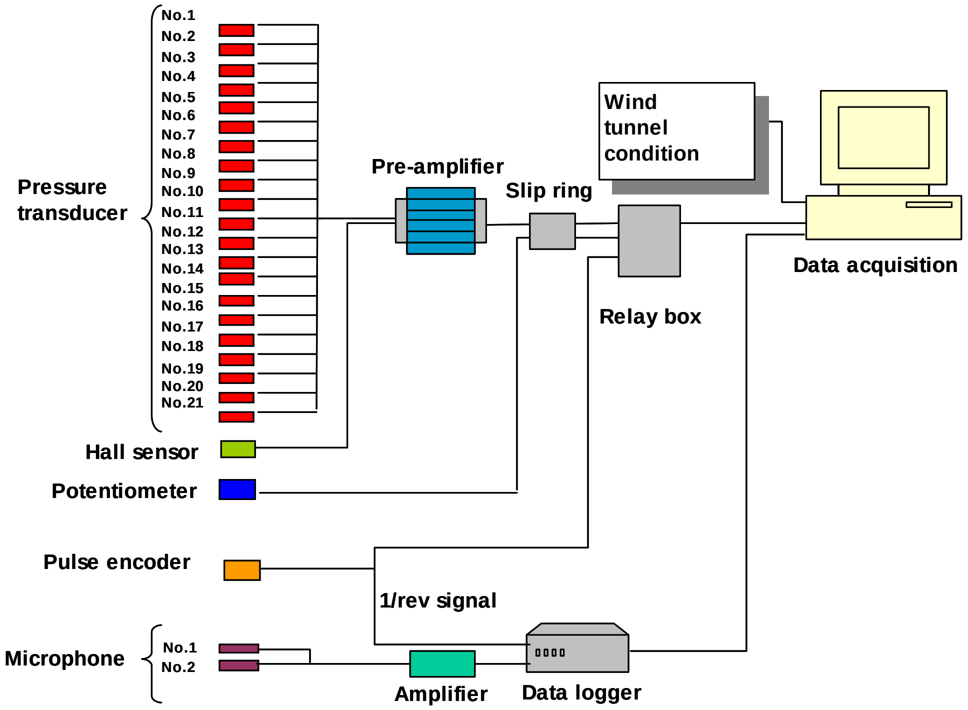


Figure 7: Measurement system

5.4 Data acquisition/procession

The above mentioned measured items are acquired simultaneously and processed with 1/rev output signals of the pulse encoder in order to be related with the rotor azimuth angle.
The sample rate for microphones is set at 10kHz and that for the others such as the blade surface pressures and Hall sensor is set at 4kHz by the limitation of data storage.

All the data acquired in the time domain are ensemble averaged of 40 revolutions equal to 4sec. in order to eliminate the random noise from the measured data and to make the periodical aeroacoustic and aerodynamic characteristics caused by rotor revolution clear.
The other details of the data acquisition/procession are described in Ref.9.

5.5 Control system for closed loop operation

Fig.8 shows the control system in the wind tunnel testing for evaluating the closed loop control law, which is installed on the 1-bladed rotor system.
Because of the mechanical limitation that the rotor system can change only AT phase automatically, the closed loop control law is applied to generate AT phase only in this study.

The measured blade pressure signal is conditioned on the rotating frame before transmitted to the non-rotating frame by a slip ring where the signal can be easily contaminated electrically. On the non-rotating frame, the conditioned blade pressure signal is ensemble averaged to minimize the electrical random noise in order to be sufficiently used as an input to the control law. Compromising between the time consumed and the data quality, 5 rotor revolutions for blade pressure signal ensemble averaging is selected based on measured data of 1,3,5,10and 20 revolutions.

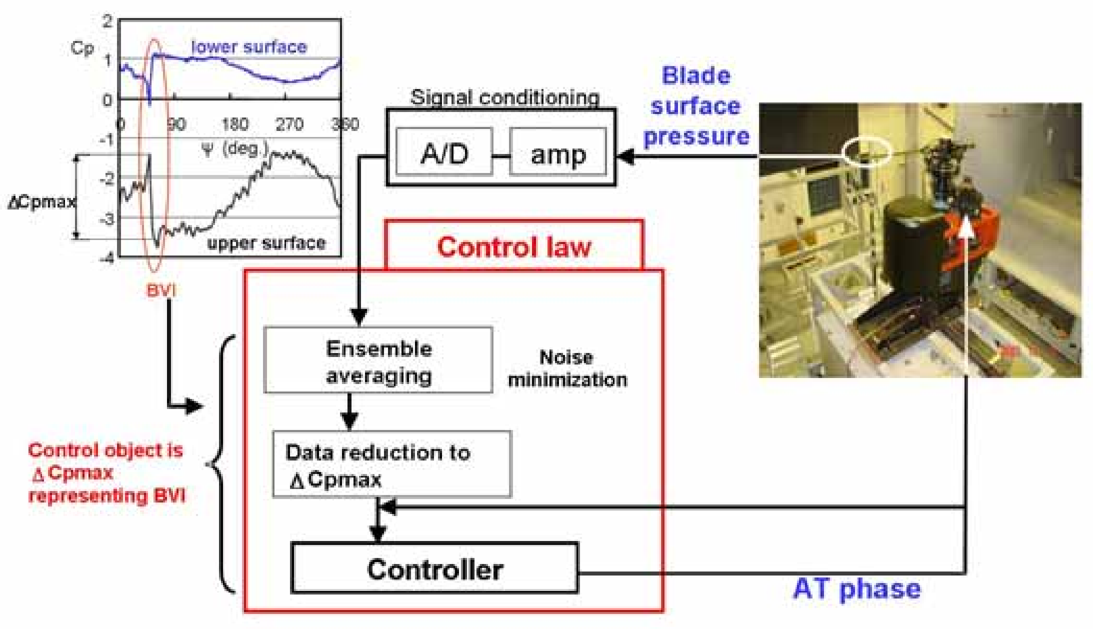


Figure 8: Control system in wind tunnel testing

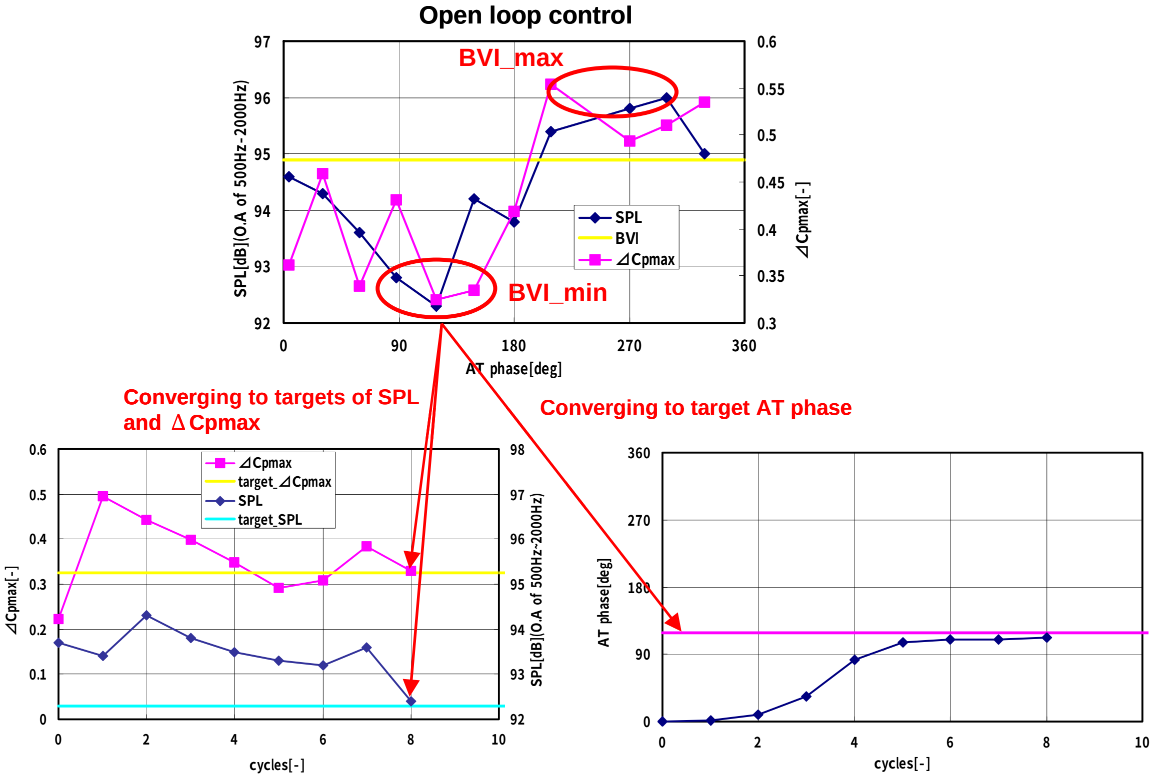
Then, the BVI index, ΔCpmax, is generated by processing the ensemble averaged blade pressure signal in a time domain and used as an input to the control law which outputs AT phase. This control cycle is repeated until the performance function sufficiently converges.
The single control cycle takes about 1sec. by this constructed software and hardware of the control system. As the priority is set on the capability for proper convergence in this stage of the study, the time period to achieve the convergence is not pursued, however, which must be a challenge in the future work.

6 RESULTS AND DISCUSSION

Fig.9 shows the wind tunnel test result of the closed loop control which utilizes ΔCpmax as an input of the control law.

The open loop test was conducted at first to investigate the target value of AT phase which can minimize BVI noise as shown in the upper side figure of Fig.9 comparing ΔCpmax with SPL. This figure indicates the correlation between blade surface pressure and sound pressure, although ΔCpmax has some fluctuation in the lower range of AT phase. It can be seen that the target value of AT phase =117deg to get maximum noise reduction on this wind tunnel test condition where AT phase generated by the closed loop control law is supposed to converge.

Then, the closed loop test was carried out to evaluate the performance of the proposed closed loop control law as shown in the lower side figures of Fig.9. The left side figure shows the converging trend of ΔCpmax to the target value obtained by the open loop test along with SPL tendency which is not control by the control law but is only monitored for confirming that ΔCpmax converges to the value where SPL simultaneously converges to its minimum value indicating the same tendency as ΔCpmax with respect to the control cycle.



Closed loop control :
SPL and ΔCpmax convergence

Closed loop control :
AT phase convergence

Figure 9: Wind tunnel test result of closed loop control

The right figure in the lower side figures of Fig.9 shows that the converging history of AT phase has fairly modest property without overshoot. Studying the Fig.9, it is shown that SPL and ΔCpmax converges to the target values and AT phase history has a good convergence property to make fully use of the noise reduction capability of Active Tab.

7 CONCLUSIONS

In this study, the blade surface pressure and the sound pressure are measured on a BVI condition by the wind tunnel test using the 1-bladed rotor system. The correlation between the blade surface pressure and the sound pressure is examined to make use the former as BVI detection index. The closed loop control law for Active Tab is proposed and developed utilizing the property of the blade surface pressure and evaluated by the wind tunnel test.
Summarizing the results of this study, the followings are concluded:

1. ΔCpmax, temporal variation of blade surface pressure, can be utilized as an input to the control law for Active Tab.

2. The proposed control law utilizing the blade surface pressure, which enables the control system to be made only by on-board sensors, successfully functioned to make use of Active Tab capability to reduce BVI noise with sufficient convergence. But it is necessary to reduce the time required by the control cycle, which is one of future works.
3. The proper procedure to process the blade pressure data as an input to a control law, which is easily contaminated by electrical noise, is developed and confirmed that the useful performance is demonstrated by the wind tunnel test.

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9 REFERENCES

[1] Hasegawa, Y., Katayama, N., Kobiki, N., Nakasato, E., Yamakawa, E., Okawa, H., “Experimental and Analytical Results of Whirl Tower Test of ATIC Full Scale Rotor System”, 57th Annual Forum of American Helicopter Society, Washington D.C., May 9-11, 2001.

[2] Straub, F., Kennedy, D., “Design, Development, Fabrication and Testing of an Active Flap Rotor System”, 61st Annual Forum of American Helicopter Society, Grapevine, TX, June 1-3, 2005.

[3] Enenkl, B., Klöppel, V., Preißler, D., “Full Scale Rotor with Piezoelectric Actuated Blade Flaps”, 28th European Rotorcraft Forum, Bristol, United Kingdom, September 17-19, 2002.

[4] Dieterich, O., Enenkl, B., Roth, D., “Trailing Edge Flaps for Active Rotor Control Aeroelastic Characteristics of the ADASYS Rotor System” 62nd Annual Forum of American Helicopter Society, Phoenix, AZ, May 9-11, 2006.

[5] Fürst, D., Keßler, C., Auspitzer, T., Müller, M., Hausberg, A., Witte, H., “Closed Loop IBC-System and Flight Test Results on the CH-53G Helicopter”, 60th Annual Forum of American Helicopter Society, Baltimore, MD, June 7-10, 2004.

[6] Kosaka, M., Saito, S., Kobiki, N., Fujita, H., “A Study of Closed Loop Control Law for BVI Noise Reduction”, Inter Noise 2005, Rio de Janeiro, Brazil, August 7-10, 2005.

[7] Kobiki, N., Kondo, N., Saito, S., Akasaka, T., Tanabe, Y., “Active Tab, a New Active Technique for Helicopter Noise Reduction”, 29th European Rotorcraft Forum, Friedrichshafen, Germany, September 16-18, 2003, Paper #50.

[8] Aoyama, T., Yang, C., Saito, S., “Numerical Analysis of BVI Noise Reduction by Active Tab”, 60th American Helicopter Society Annual Forum, Baltimore, MD, June 7-10, 2004.

[9] Kobiki, N., Kondo, N., Saito, S., Akasaka, T., Tanabe, Y., “An Experimental Study of On-blade Active Tab for Helicopter Noise Reduction”, 30th ERF, France, September 2004.

[10] Kobiki, N., Saito, S., Akasaka, T., Tanabe, Y., Fuse, H., “An Experimental Study for Aerodynamic and Acoustic Effects of On-blade Active Tab”, 31st ERF, Italy, September 2005.

[11] Fuse, H., Fujita, H., Kobiki, N., Saito, S., “A Research on Control Object for BVI Noise Reduction with Active Techniques”, 2005 JSASS-KSASS Joint International Symposium on Aerospace Engineering, Nagoya, Japan, October 2005.

[12] Kobiki, N., Tsuchihashi, A., Murashige A., Yamakawa, E., “ Elementary Study for the

Effect on HHC and Active Flap on Blade Vortex Interaction ”, 23rd European Rotorcraft Forum, Dresden, Germany, September 1997, Paper 29.